

# Quantitative Study of Magnetotransport through a (Ga,Mn)As Single Ferromagnetic Domain

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(Dated: February 2, 2008)

We have performed a systematic investigation of the longitudinal and transverse magnetoresistance of a single ferromagnetic domain in  $\text{Ga}_{1-x}\text{Mn}_x\text{As}$ . We find that, by taking into account the intrinsic dependence of the resistivity on the magnetic induction, an excellent agreement between experimental results and theoretical expectations is obtained. Our findings provide a detailed and fully quantitative validation of the theoretical description of magnetotransport through a single ferromagnetic domain. Our analysis furthermore indicates the relevance of magneto-impurity scattering as a mechanism for magnetoresistance in  $\text{Ga}_{1-x}\text{Mn}_x\text{As}$ .

PACS numbers: 75.47.-m, 75.50.Pp, 75.70.Ak

The resistance of ferromagnetic materials is a function of the relative orientation between the magnetization  $\mathbf{M}$  and the current density  $\mathbf{j}$ . In general, the orientation of  $\mathbf{M}$  depends on the externally applied magnetic field, which results in an anisotropic magnetoresistance (AMR) characteristic of ferromagnets[1, 2]. Although a vast amount of work has been devoted to the study of this magnetization-induced AMR in the past, a complete quantitative analysis of the magnetoresistive behavior of a single ferromagnetic domain has not been performed yet.

It was found theoretically long ago from simple symmetry considerations that, for isotropic materials, the AMR of a single ferromagnetic domain can be described by the two equations[1, 2]

$$E_{\text{long}} = j\rho_{\text{long}} = j\rho_{\perp} + j(\rho_{\parallel} - \rho_{\perp})\cos^2\phi_M, \quad (1)$$

$$E_{\text{trans}} = j\rho_{\text{trans}} = j(\rho_{\parallel} - \rho_{\perp})\sin\phi_M\cos\phi_M. \quad (2)$$

Here,  $E_{\text{long}}$  and  $E_{\text{trans}}$  are the components of the electric field along and perpendicular to  $\mathbf{j}$ ,  $\rho_{\parallel}$  and  $\rho_{\perp}$  are the value of resistivity measured when  $\mathbf{j} \parallel \mathbf{M}$  and  $\mathbf{j} \perp \mathbf{M}$ , and  $\phi_M$  is the angle between  $\mathbf{M}$  and  $\mathbf{j}$ . These equations – to which we will refer to as the single domain magnetoresistance (SDM) model – are expected to account for the behavior of the longitudinal *and* the transverse voltage drop generated by a current flowing through a ferromagnet. Given that the relative orientation between  $\mathbf{j}$  and  $\mathbf{M}$  is known, the only quantities that are needed to describe the (in general) complex AMR behavior observed experimentally are  $\rho_{\parallel}$  and  $\rho_{\perp}$ .

In conventional metallic ferromagnets such as Ni or Co, a full quantitative validation of the SDM model is diffi-

cult. Extensive investigations of the longitudinal magnetoresistance have been performed, but the relatively small magnitude of the transverse (Hall-like) signal prevents a precise quantitative comparison of experimental data to Eq. (2). In the ferromagnetic semiconductor  $\text{Ga}_{1-x}\text{Mn}_x\text{As}$ , the situation is different. A very large transverse electric field ("giant" planar Hall effect) has been recently reported[3] and its dependence on the magnetization orientation found to be in excellent quantitative agreement with the predictions of Eq. (2). However, the very rich behavior of the longitudinal electric field has not been quantitatively analyzed so far.

In this paper, we investigate magnetotransport through a single domain of  $\text{Ga}_{1-x}\text{Mn}_x\text{As}$  to perform a detailed and complete test of Eq. (1) and (2) of the SDM model. Our work is based on measurements of the longitudinal and transverse magnetoresistance for many different orientations of the applied in-plane magnetic field. Specifically, we first analyze a selected set of these measurements to determine the parameters of the SDM model, including a linear dependence of  $\rho_{\parallel}$  and  $\rho_{\perp}$  on the magnetic induction  $\mathbf{B}$  (i.e.,  $\rho_{\perp}, \rho_{\parallel} \propto -\mu_0|\mathbf{H} + \mathbf{M}|$ ). We then use the values of the parameters so determined to perform a fully quantitative comparison between the predictions of the SDM model and magnetotransport measurements in arbitrary orientations of the in-plane magnetic field. We find an excellent agreement between theory and experiments in all cases, for *both* the longitudinal and the transverse magnetoresistance. The results presented here conclusively demonstrate the full quantitative validity of the SDM model, and confirm that the low-field AMR in  $\text{Ga}_{1-x}\text{Mn}_x\text{As}$  is determined by one single domain reversing its orientation via abrupt switches of approximately  $90^\circ$  [3, 4, 5]. In addition, our findings also indicate the relevance of magneto-impurity scattering as a source of intrinsic magnetoresistance in  $\text{Ga}_{1-x}\text{Mn}_x\text{As}$ .

The  $\text{Ga}_{1-x}\text{Mn}_x\text{As}$  thin films studied were grown by molecular beam epitaxy on (100)-oriented, semi-insulating GaAs wafers. Here, we will focus on a sam-

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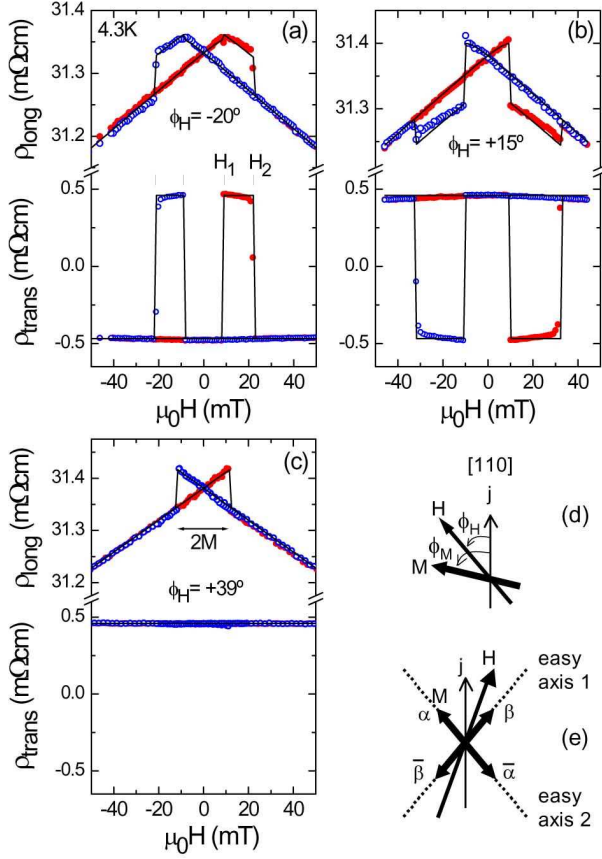


FIG. 1: Panels (a-c) show the longitudinal and transverse magnetoresistance of a single  $\text{Ga}_{1-x}\text{Mn}_x\text{As}$  ferromagnetic domain, measured for three different orientations of the in-plane magnetic field ( $\phi_H = -20^\circ$ ,  $+15^\circ$ , and  $+39^\circ$ , respectively). In all panels, full symbols represent the data measured for an increasing magnetic field  $H$  (up-sweep) and the open symbols those measured with a decreasing field (down-sweep). The full lines represent the resistances calculated from Eqs. (1) and (2), as discussed in the text. Panel (d) defines the angles  $\phi_H$  and  $\phi_M$  between the field  $\mathbf{H}$ , the magnetization  $\mathbf{M}$ , and the current density  $\mathbf{j}$ . Panel (e) illustrates the orientation of the two easy axes in  $\text{Ga}_{1-x}\text{Mn}_x\text{As}$  with respect to the direction of the current flow. When the field  $H$  is swept, magnetization reversal occurs by subsequent,  $\approx 90^\circ$ -switches, e.g.  $\beta \rightarrow \bar{\alpha} \rightarrow \bar{\beta}$ .

ple with Mn content  $x = 0.07$ , thickness  $d = 57$  nm, and Curie temperature  $T_C \approx 80$  K. The thin film was patterned into  $200 \times 50 \mu\text{m}^2$  Hall bar mesas using photolithography and wet chemical etching, with the long axes of the Hall bars aligned along the crystallographic [110] direction to within experimental accuracy. For the magnetotransport experiments, the samples were mounted on a rotatable sample holder and inserted into the He cryostat of a superconducting magnet.  $\rho_{\text{long}}$  and  $\rho_{\text{trans}}$  were simultaneously recorded in ac current-bias 4-probe measurements, using a lock-in technique. In all experiments discussed here, the external magnetic field

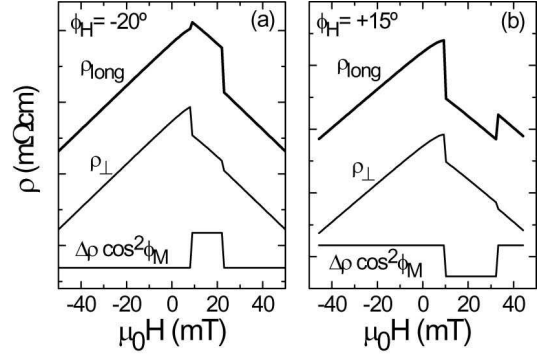


FIG. 2: Panel (a) and (b) illustrate the behavior of the different contributions to the longitudinal magnetoresistance (thin lines) as well as their sum (i.e., the total longitudinal resistance; thick line), as calculated from Eq. (1) for two different orientations of the in-plane field ( $\phi_H = -20^\circ$  and  $+15^\circ$ ). All the traces are offset for clarity. The first term,  $\rho_\perp$ , is proportional to the magnitude of the magnetic induction vector. The second term,  $(\rho_\parallel - \rho_\perp) \cos^2(\phi_M) = \Delta\rho \cos^2(\phi_M)$ , reflects the abrupt switches of  $\phi_M$ . A comparison between calculations and experimental data is shown in Fig. 1(a,b) and in Fig. 3.

$\mathbf{H}$  was applied in the plane of the thin film. The rotatable holder enabled us to choose the angle  $\phi_H$  between  $\mathbf{j}$  and  $\mathbf{H}$  (see Fig. 1(d)) with an accuracy of about  $1^\circ$ .

The rich features in the low-field, anisotropic magnetoresistance of  $\text{Ga}_{1-x}\text{Mn}_x\text{As}$  are illustrated in Figure 1, which shows the magnetoresistance measured for three different orientations of the in-plane magnetic field. It is apparent that the shape of the observed magnetoresistance, which is in general hysteretic as expected for a ferromagnet, strongly depends on the field direction. Whereas  $\rho_{\text{trans}}$  only switches between two different and approximately constant levels (of  $\approx \pm 0.45$  mOhmcm),  $\rho_{\text{long}}$  exhibits a more complex behavior. Note, in particular, that even for those field orientations in which  $\rho_{\text{trans}}$  does not show any dependence on  $H$  ( $\phi_H = +39^\circ$ , Fig. 1(c)), a strong field dependence as well as hysteresis are still present in  $\rho_{\text{long}}$ . While similar observations have already been reported, no full quantitative analysis has been performed: the complexity of the behavior of the longitudinal magnetoresistance demonstrates that for the validation of the SDM model, a careful test of both Eq. (1) and (2) is needed.

The analysis of the transverse magnetoresistance signal and the comparison to Eq. (2) is identical to what has been discussed by Tang *et al.* in Ref. [3], to which we refer the reader for details. Here, we simply summarize the results which are needed in the analysis of the longitudinal magnetoresistance.[3, 4, 5, 6, 7] In particular, the transverse in-plane magnetoresistance and its dependence on the orientation of the external magnetic field can be completely understood in terms of abrupt changes of the magnetization orientation in the  $\text{Ga}_{1-x}\text{Mn}_x\text{As}$  layer. At low temperature and in the magnetic field range used in our experiments, the magnetization is always parallel or anti-

parallel to one of the two easy magnetic axes. These axes point approximately along the  $[100]$  and  $[010]$  directions (Fig. 1(e)). When the magnetic field is swept, magnetization reorientation occurs via the nucleation and rapid expansion of a  $90^\circ$  domain.[4] On the time scale of magneto-transport experiments, this process appears as an abrupt switch of the direction of  $\mathbf{M}$ . It takes place when the energy gained by the magnetization reorientation becomes larger than a fixed domain wall pinning energy. From the analysis of the transverse magnetoresistance in our samples, we find that the orientations of the two easy axes correspond to  $\phi_H = +39^\circ$  (direction  $\alpha$  in Fig. 1(d)) and  $\phi_H = -42^\circ$  (direction  $\beta$ ). The fields  $H_1$  and  $H_2$ , at which the magnetization switches, are quantitatively consistent with the above magnetization reorientation picture for all field orientations  $\phi_H$ . Finally, from the analysis of  $\rho_{\text{trans}}$  we obtain that  $\rho_{\parallel} - \rho_{\perp} = 0.96 \text{ m}\Omega\text{cm}$ , independent of  $H$ . All these results fully agree with the findings of Ref. [3] and validate Eq. (2).

We now proceed to the analysis of  $\rho_{\text{long}}$ . We start by considering the simplest case, in which the applied magnetic field is oriented along one of the easy axes (e.g.,  $\phi_H = +39^\circ$ ; see Fig. 1(c)). In this case, upon sweeping the external magnetic field, the magnetization simply reverts its direction ( $H_1 = H_2$ , and  $\phi_M$  switches from  $+39^\circ$  to  $(39 + 180)^\circ$ ). As a consequence, the  $\cos^2(\phi_M)$  term in Eq. (1), as well as the  $\sin(\phi_M) \cos(\phi_M)$  term in Eq. (2), are constant upon magnetization reversal. This is indeed observed experimentally in the behavior of  $\rho_{\text{trans}}$ , which is exactly constant for this particular orientation of the external field (see Fig. 1(c)). Nevertheless, it is apparent from Fig. 1(c) that a linear magnetoresistance, as well as resistance jumps at the magnetic field values for which  $\mathbf{M}$  reverses, still are present in  $\rho_{\text{long}}$ . Since the second term on the right-hand side of Eq. (1) does not vary with  $H$ , we conclude that the linear magnetoresistance and the jumps observed experimentally in  $\rho_{\text{long}}$  originate from a magnetic field dependence of  $\rho_{\perp}$ , i.e., the first term on the right-hand side of Eq. (1).

The observed behavior can be understood if  $\rho_{\perp}$  is a function of  $B = |\mu_0(\mathbf{H} + \mathbf{M})|$ , since then the reversal of  $\mathbf{M}$  results in an abrupt change of  $B$  and, consequently, of  $\rho_{\perp}$ . To reproduce the experimental data, we take  $\rho_{\perp}(B) = a + b \times B$  with  $a = 30.85 \text{ m}\Omega\text{cm}$  and  $b = -3.06 \text{ m}\Omega\text{cm/T}$ . The continuous line superimposed on top of the  $\rho_{\text{long}}$  data in Fig. 1(c) illustrates the precision with which the chosen  $\rho_{\perp}(B)$  reproduces the experimental data for  $\phi_H = +39^\circ$ . In what follows, we will use this dependence of  $\rho_{\perp}$  on  $B$  to analyze the longitudinal magnetoresistance for all the other field orientations, with *one and the same value of the parameters  $a$  and  $b$  given above*. The microscopic origin of the  $B$ -dependence of  $\rho_{\perp}$  will be discussed at the end.

We also note that the linear dependence of  $\rho_{\perp}$  on  $B$  allows us to extract the magnitude of  $\mathbf{M}$  in our samples. In particular, it follows from the linear dependence of  $\rho_{\perp}$  on  $B$  that the difference in  $H$  between the two jumps in  $\rho_{\text{long}}$  corresponds to  $2M$  (Fig. 1(c)). The magnetization thus

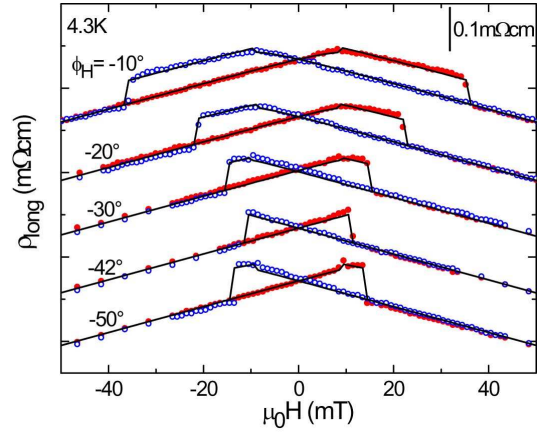


FIG. 3: Comparison between the longitudinal magnetoresistance measured for different orientations  $\phi_H$  of the magnetic field (symbols) and the predictions by Eq. (1) of the SDM model (full lines) in which all parameters have been fixed by our analysis. The magnetoresistance traces have been offset for clarity. Full symbols represent the experimental data measured for magnetic field up-sweeps, open symbols correspond to the data measured for magnetic field down-sweeps.

obtained is  $\mu_0 M = 12 \text{ mT}$ , which is somewhat smaller than the saturation magnetization that one would expect from the nominal Mn content  $x = 0.07$  assuming that all the spins are aligned. Such a magnetization deficit is often observed in  $\text{Ga}_{1-x}\text{Mn}_x\text{As}$ . [8, 9, 10]

The analysis of  $\rho_{\perp}$  for  $\phi_H = +39^\circ$  and of  $\rho_{\text{trans}}$  completely determines all quantities entering Eq. (1) and (2). We thus can now check if the SDM model reproduces the magnetoresistance behavior observed experimentally for arbitrary orientations of the applied in-plane magnetic field. We emphasize that at this point, there are no adjustable parameters: we just use the SDM model to calculate the magnetoresistance and see if the theoretical curves match the experimental ones. To illustrate how the theoretical curves are calculated, we have plotted the different terms on the right-hand side of Eq. (1) separately in Fig. 2 for two specific orientations  $\phi_H$  of the external magnetic field.

The behavior of the  $\cos^2 \phi_M$ -term is completely analogous to the  $\sin \phi_M \cos \phi_M$ -term in Eq. (2). It reflects the abrupt changes in the magnetization orientation  $\phi_M$  as the field is swept. When the magnetization switches from one easy axis to the other at the fields  $H_1$  and  $H_2$ , the magnitude of  $(\rho_{\parallel} - \rho_{\perp}) \cos^2 \phi_M$  abruptly changes, resulting in square-like steps. The behavior of the first term,  $\rho_{\perp}(B)$ , is different. Because  $\rho_{\perp}(B) \propto |\mathbf{H} + \mathbf{M}|$ , this term retraces the magnitude of the magnetic induction vector. The abrupt reorientations of  $\mathbf{M}$  also lead to abrupt steps in  $|\mathbf{H} + \mathbf{M}|$ , the magnitude of which is different for different orientations of  $\mathbf{H}$ , due to the vectorial addition of  $\mathbf{M}$  and  $\mathbf{H}$ . Because the magnitude of  $M$  and  $H$  as well as their orientations are known,  $|\mathbf{H} + \mathbf{M}|$  and thus also  $\rho_{\perp}(B)$ , can be calculated. Taken together, the interplay of the two terms on the right side of Eq. (1)

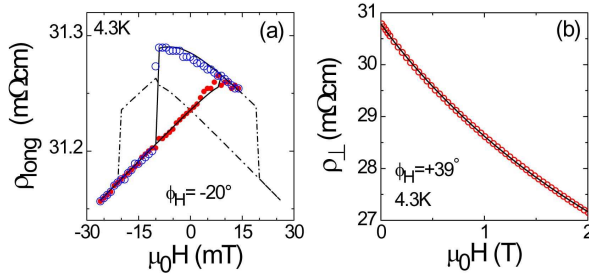


FIG. 4: (a) Longitudinal magnetoresistance measured ramping up (full circles) and down (open circles) the magnetic field, reverting the sweep direction at 15 mT, i.e., in between the two switches of the magnetization orientation. The full line is calculated theoretically using Eq. (1) of the SDM model, without any adjustable parameters (all parameters are fixed by the previous analysis). The dash-dotted line illustrates the magnetoresistance obtained if the field sweep direction is reversed after the second switch of the magnetization orientation (see also Fig. 1(a)). (b) The magnetic field dependence of  $\rho_{\perp}$  measured experimentally (open symbols) is reproduced by the magneto-impurity scattering model proposed by Nagaev (full line) over a broad range of magnetic fields.

results in the qualitatively different shape of  $\rho_{\text{long}}$  for different orientations of the magnetic field (Fig. 2).

The  $\rho_{\text{long}}$  and  $\rho_{\text{trans}}$  calculated from the SDM model are shown as full lines in Figs. 1(a,b) and 3. For all orientations  $\phi_H$  of the external magnetic field, the SDM model quantitatively describes the longitudinal resistance observed in experiment. In particular, both the strongly varying magnitude and shape of the switches observed in  $\rho_{\text{long}}$  are precisely reproduced in the calculations. This demonstrates that Eqs. (1) and (2) yield a fully quantitative description of the low-field AMR of  $\text{Ga}_{1-x}\text{Mn}_x\text{As}$  for all orientations  $\phi_H$  of the external magnetic field.

The agreement between the SDM model and the experiment can be tested even further by analyzing magnetoresistance measurements in which the direction of the magnetic field sweep is reversed after the first, but before the second magnetization switch. In this case, for small values of  $H$ ,  $\mathbf{M}$  points along one easy axis in the up sweep and along the other in the down sweep. As a consequence, the magnetoresistance traces for the up and the down sweep are different, as illustrated in Fig. 4(a). Again, an excellent agreement between the SDM model and experiment is found, with no adjustable parameters. This

agreement confirms our hypothesis that  $\rho_{\perp}(B) \propto -|\mathbf{B}|$ , since around  $H = 0$ , the magnetoresistance only originates from a change in the vectorial sum  $\mu_0(\mathbf{H} + \mathbf{M})$ .

We now briefly discuss the microscopic origin of the experimentally observed  $B$ -dependence of  $\rho_{\perp}$  (as well as of  $\rho_{\parallel}$ , since  $\rho_{\perp} - \rho_{\parallel} = \text{const.}$ ). Although several different mechanisms, such as weak localization, spin-disorder scattering, and variable-range hopping give rise to a magnetic field dependent resistivity,[8, 11, 12, 13, 14] none of them predicts a linear negative magnetoresistance. However, it was found recently by Nagaev[15, 16] that spin-dependent scattering at magnetic impurities can result in a negative magnetoresistance of the form  $\rho(B) = a - bB + cB^{3/2}$ . This functional dependence correctly describes our experimental data not only in the linear regime that we have discussed here extensively, but also for higher field values, where a non-linear dependence is experimentally visible (see Fig. 4(b)). This observation, in conjunction with recent investigations of the resistance temperature dependence[17], indicates the relevance of magneto-impurity scattering in  $\text{Ga}_{1-x}\text{Mn}_x\text{As}$ . In the future, a systematic comparison between experimental data and the magneto-impurity model will be needed to establish up to which extent this theory describes the intrinsic magnetoresistance of  $\text{Ga}_{1-x}\text{Mn}_x\text{As}$ . The quantitative understanding of anisotropic magnetoresistance reached in our work makes it possible to separate the magnetization-related AMR from the intrinsic magnetoresistance ( $\rho_{\parallel}, \rho_{\perp}$ ), thus enabling a detailed study of the latter.

In summary, we have investigated experimentally the longitudinal and transverse magnetoresistance in a single ferromagnetic domain of  $\text{Ga}_{1-x}\text{Mn}_x\text{As}$  and performed a comprehensive theoretical analysis of the experimental results. We find that, by taking into account the intrinsic dependence of the resistivity on the magnetic induction, excellent quantitative agreement between experiments and theory is obtained. Our results provide the first detailed and fully quantitative validation of the theory for magnetotransport through a single ferromagnetic domain. In addition, our analysis indicates the relevance of magneto-impurity scattering in  $\text{Ga}_{1-x}\text{Mn}_x\text{As}$ .

The authors gratefully acknowledge stimulating discussions with G. E. W. Bauer and R. Gross. The work of A.F.M. and of S.T.B.G. is part of the NWO Vernieuwingsimpuls 2000 program.

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